



Tuning quadratic nonlinear photonic crystal fibers for zero group-velocity mismatch

Bache, Morten; Lægsgaard, Jesper; Bang, Ole

Published in:

Conference on Lasers and Electro-Optics and 2006 Quantum Electronics and Laser Science Conference. CLEO/QELS 2006.

Link to article, DOI:

[10.1109/CLEO.2006.4628232](https://doi.org/10.1109/CLEO.2006.4628232)

Publication date:

2006

Document Version

Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Bache, M., Lægsgaard, J., & Bang, O. (2006). Tuning quadratic nonlinear photonic crystal fibers for zero group-velocity mismatch. In *Conference on Lasers and Electro-Optics and 2006 Quantum Electronics and Laser Science Conference. CLEO/QELS 2006*. (pp. 1-2). IEEE. <https://doi.org/10.1109/CLEO.2006.4628232>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Tuning Quadratic Nonlinear Photonic Crystal Fibers for Zero Group-Velocity Mismatch

Morten Bache, Jesper Lægsgaard, and Ole Bang

COM•DTU Department of Communications, Optics & Materials, Technical University of Denmark, Bld. 345v, DK-2800 Lyngby, Denmark. Tel: +45 4525 3775, fax: +45 4593 6581

Morten Bache's e-mail address: bache@com.dtu.dk

Abstract: A nonlinear index guiding silica PCF is optimized for efficient second harmonic generation through dispersion calculations. Zero group velocity mismatch is possible for any pump wavelength above 80 nm. Very high conversion efficiencies and bandwidths are found.

©200 Optical Society of America

OCIS codes: 0 0 2280 Fiber design and fabrication; 0 0 2400 Fiber properties; 0 0 43 0 Nonlinear optics: fibers

Relying on quadratic nonlinearities, second harmonic generation (SHG) is widely used for efficient wavelength conversion devices in order to extend the spectral range of laser sources and to do all optical wavelength multiplexing. Efficient conversion from the fundamental to the second harmonic (SH) mode requires a small phase mismatch between them. Phase matching to the lowest order is typically achieved through a quasi phase matching (QPM) technique [1] whereby the group velocity mismatch (GVM) sets the limits to device length and bandwidth for pulsed SHG. In conventional fibers, SHG with near zero GVM was found for restricted wavelengths [2] while zero GVM was predicted using mode matching [3]. For bulk media, zero GVM was found for restricted wavelengths by spectrally noncritical phase matching [4] and by combining non collinear QPM with a pulse front tilt [5].

Here we investigate efficient pulsed SHG in a poled silica photonic crystal fiber (PCF) having a standard index guiding triangular design with a single rod defect in the center. The main design parameters of the PCF are the pitch Λ and the relative hole diameter $D=d/\Lambda$. The nonlinearity is induced, e.g., by thermal poling as has recently been demonstrated in PCFs [6]. We tune the phase matching properties of SHG by exploiting the flexibility that PCFs offer in designing the dispersion properties [7]. Previous investigations [8] of SHG in PCFs considered the scalar case and found large bandwidths and strong modal overlaps for selected parameter values. Instead, we perform a detailed vectorial analysis over a continuous parameter space and show zero GVM for any fundamental wavelength $\lambda_1 > 80$ nm by merely adjusting Λ and D . This is a much simpler way of removing GVM compared to previous methods [3–5]; it promises very large bandwidths due to its flexibility and it is very efficient.

A fiber mode can be described by an effective index $n_{\text{eff}} = c/v_{\text{ph}}$, i.e., the ratio of the speed of light c to the phase velocity of the mode $v_{\text{ph}} = \omega/\beta$ with β the propagation constant of the mode. The dispersive character of β gives a phase velocity mismatch between the fundamental (ω_1) and SH ($\omega_2 = 2\omega_1$) modes, which we classify through the index mismatch $\Delta n = c[1/v_{\text{ph}}(\omega_1) - 1/v_{\text{ph}}(\omega_2)] = c(\beta_1/\omega_1 - \beta_2/\omega_2)$ related to the phase mismatch $\Delta\beta = 2\beta_1 - \beta_2$ as $\Delta n = \Delta\beta\lambda_1/4\pi$. The group velocity is instead defined as $1/v_g = \partial\beta/\partial\omega$, giving a GVM (walk off) parameter $d_{12} = 1/v_g(\omega_1) - 1/v_g(\omega_2)$.

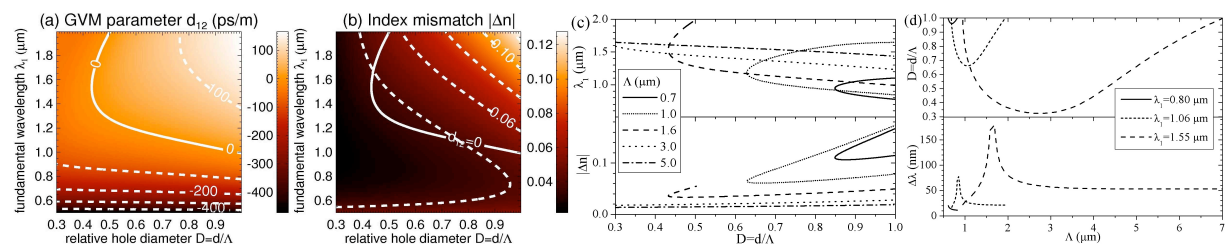


Fig. 1 (a) GVM and (b) index mismatch in D and λ_1 space keeping $\Lambda = 1 \mu\text{m}$ fixed. The solid contour in (a) indicates zero GVM. (c) shows zero GVM contours for different Λ s (upper) and the corresponding index mismatch along the zero GVM contour (lower). (d) shows the D value as function of Λ that gives zero GVM for some selected pump wavelengths as well as the corresponding SHG bandwidth for a 10 cm fiber.

We calculated the dispersion with the MIT Photonic Bands (MPB) package [9]. A perturbative approach [10] was used to introduce chromatic dispersion, allowing us to calculate data once over a large parameter space for Λ unity and perturbatively calculate the changes as Λ was varied. The result of the dispersion calculations is shown in Fig. 1. The GVM and index mismatch are shown in Fig. 1(a, b) in the (D, λ_1) parameter space, keeping the pitch fixed at $\Lambda = 1 \mu\text{m}$. Along the solid contour $d_{12} = 0$; thus, zero GVM is possible for any $\lambda_1 > 1 \mu\text{m}$ by choosing a proper D . Fig. 1(c) underlines that this is a general trend: there the zero GVM contour is shown for selected pitches, and we found $d_{12} = 0$ can be achieved for any $\lambda_1 > 80$ nm. Figure 1(b) shows that zero index mismatch can never be achieved, even with non zero GVM. This holds also for other pitches, so efficient SHG will require additional phase matching.

such as QPM (typical QPM grating periods $2l_{\text{coh}} = 2\pi |\Delta\beta| = \lambda_1 / 2|\Delta n|$ range from 5–100 μm) Figure 1 (c) shows the values of the index mismatch as the zero GVM contour is traversed. For $\Lambda = 0, 0.1, 0$ and $1 \mu\text{m}$ a cusp appears around $\lambda_1 \sim \Lambda$ after which $|\Delta n|$ increases with λ_1 . This is because the fundamental mode is no longer well confined in the core while the SH having a smaller wavelength is still well confined. Conversely for the considered wavelengths the modes are always well confined for larger pitches explaining why a small $|\Delta n|$ is observed there.

Focusing on the telecom Nd:AG and Ti:Sapphire operating wavelengths ($\lambda_1 = 1.55, 1.0$ and $0.8 \mu\text{m}$ respectively) Fig. 1 (d) shows the D value required to get zero GVM as Λ is changed. For $\lambda_1 = 0.80 \mu\text{m}$ zero GVM requires very large D values e.g. $D = 0.9$ for $\Lambda = 0.0 \mu\text{m}$. For such D values deviations from the ideal circular holes must be expected which might influence the results. We still highlight the results because SHG with zero GVM for $\lambda_1 = 0.80 \mu\text{m}$ is not obtainable in standard nonlinear materials. For $\lambda_1 = 1.0 \mu\text{m}$ the lowest required D values are in a range where the ideal round holes should be preserved. The curves stop for larger Λ because it is no longer possible to get $d_{12} = 0$ (it would require $D > 1$ which is unphysical). For $\lambda_1 = 1.55 \mu\text{m}$ a large D can be found for both large and small pitches but $\Lambda < 2 \mu\text{m}$ is preferred because the core is smaller leading to higher intensities. In Fig. 1(d) we calculate the SHG bandwidth $\Delta\lambda$ by expanding $\Delta\beta$ around λ_1 up to third order and assuming that a QPM grating compensates the lowest order term (as in conventional fibers [2]). Since we have $d_{12} = 0$ the 2nd order dispersion dominates yielding very large bandwidths. Moreover because $d_{12} = 0$ the bandwidth of a fiber with length l_F scales as $\Delta\lambda \propto l_F^{-1/2}$ (instead of $\Delta\lambda \propto l_F^{-1}$ when $|d_{12}| > 0$) so a longer device can be created without losing too much bandwidth. Note also in Fig. 1(a) the turn of the zero GVM contour around $D = 0.43$ and $\lambda_1 = 1.55 \mu\text{m}$ implying that the 2nd order contributions to the bandwidth term vanish giving an increasing bandwidth as observed in Fig. 1(d).

Using the reductive perturbation method [11] and assuming that the dimensionless (DL) propagating fields $u_j(z, t)$ can be decoupled from the DL transverse MPB modes $\mathbf{e}(\mathbf{x})$ the DL nonlinear equations for SHG are

$$(\partial_z - iD_1\partial_t^2)u_1 = i\sigma u_1^* u_2 e^{-i\Delta\beta z/l_F} \quad (\partial_z - d_{12}l_F\tau^{-1}\partial_t - iD_2\partial_t^2)u_2 = i\sigma u_1^2 e^{i\Delta\beta z/l_F} \quad 2D_j = l_F(2\tau^2)\partial_\omega^2\beta_j$$

$$\sigma = \rho l_F \sqrt{2\hbar\omega_1^2\omega_2} n_1^2 n_2 \epsilon_0 c^3 \tau \quad \rho = \left| \int d\mathbf{x} \mathbf{e}_1^*(\mathbf{x}) \cdot \tilde{\chi}^{(2)} : \mathbf{e}_2(\mathbf{x}) \mathbf{e}_1^*(\mathbf{x}) \right| (\Lambda a_1 a_2^{-1})^2 \quad a_j = \int d\mathbf{x} |\mathbf{e}_j(\mathbf{x})|^2$$
(1)

z is scaled to l_F , t to the input pulse length τ and $\mathbf{x} = (x, y)$ to the pitch Λ . Integrating $|u_j(z, t)|^2$ over time gives the photon number of the mode. The DL nonlinear coefficient σ was found to scale as $\sigma \propto D/\Lambda$: a large D gives a better mode confinement and a large overlap integral $\propto \rho$ and decreasing Λ gives a smaller core and thus a larger ρ . Integrating Eqs. (1) under assumption of a continuous wave and undepleted fundamental the SHG efficiency is $\eta = P_2/P_1 = P_1 \tau \sigma^2 \text{sinc}^2(\Delta\beta l_F/2)$. $2\hbar\omega_1 \propto P_1 \rho^2 l_F^2 \text{sinc}^2(\Delta\beta l_F/2)$ where $P_j = \hbar\omega_j |u_j|^2 \tau$ is the mode power. In Table 1 some designs are then shown for selected λ_1 values assuming a realistic poling strength of 1 pm/V in the main direction of the $\chi^{(2)}$ tensor (the xxx direction). We find bandwidths large enough to convert down to $\tau_{\text{lim}} = 21$ fs pulses and very high relative efficiencies $\eta' = \eta P_1 l_F^2$ ranging from 5–250 % (W·cm²).

Table 1 Efficient SHG with zero GVM. Input pulse length $\tau = 1$ ps, $l_F = 10$ cm, main component of $\chi^{(2)}$ tensor 1 pm/V

λ_1 [μm]	Λ [μm]	D	$\Delta\lambda$ [nm]	τ_{lim} [fs]	$ l_{\text{coh}} $ [μm]	$\sigma \cdot 10^4$	ηP_1 [% mW]	$\eta' = \eta P_1 l_F^2$ [% (W·cm ²)]
0.80	0.0	0.9	13	3	2.1	112	25	250
1.0	0.85	0.2		21	3	49.8	3	3
1.55	1.0	0.43	1.0	21	14.4	11.5	0.5	5.0

Summarizing silica index guiding PCFs can be designed for efficient SHG with zero GVM for any fundamental wavelength above 80 nm simply by tuning the pitch and relative diameter of the air holes. The design examples focused on important wavelengths of optical components: we found very high bandwidths (large enough for 21 fs pulse conversion) and very high efficiencies [5–250 % (W·cm²)] giving great promise for frequency conversion of short pulses with fibers. Poling of PCFs have already been demonstrated [] so such fibers can readily be made once the QPM grating techniques have been successfully transferred from standard fibers to PCFs.

[1] M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, IEEE J. Quantum Electron. **28**, 2–31 (1992).

[2] P. G. Kazansky and V. Pruneri, J. Opt. Soc. Am. B **14**, 31–0 (1997).

[3] A. Arraf and C. M. de Sterke, IEEE J. Quantum Electron. **34**, 0 (1998).

[4] N. E. u J. H. Ro, M. Cha, S. Kurimura, and T. Taira, Opt. Lett. **27**, 104 (2002).

[5] S. Ashihara, T. Shimura, and K. Kuroda, J. Opt. Soc. Am. B **20**, 853 (2003).

[] D. Faccio, A. Busacca, W. Belardi, V. Pruneri, P. Kazansky, T. Monro, D. Richardson, B. Grappe, M. Cooper, and C. Pannell, Electron. Lett. **37**, 10 (2001).

[] A. Ferrando, E. Silvestre, J. Miret, and M. Andrés, Opt. Express **9**, 8 (2000).

[8] T. M. Monro, V. Pruneri, N. G. R. Broderick, D. Faccio, P. G. Kazansky, and D. J. Richardson, IEEE Photon. Tech. Lett. **13**, 981 (2001).

[9] S. Johnson and J. Joannopoulos, Opt. Express **8**, 1–3 (2001).

[10] J. Lægsgaard, A. Bjarklev, and S. Libori, J. Opt. Soc. Am. B **20**, 443 (2003).

[11] Kodama and A. Hasegawa, IEEE J. Quant. Electr. **QE-23**, 510 (1987).